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GLOBAL POSITIONING SYSTEM: PAST AND FUTURE APPLICATIONS

Yuan Jianping

ABSTRACT: The article describes in general terms the development of the global positioning system (GPS), as well as its applications in aeronautics, astronautics, oceanic navigation, geodetic surveying, earthquake prediction, land navigation guidance, and military science. The article presents briefly progress in GPS in China. In closing, GPS research, development, and its relationship to flight mechanics are discussed.

KEY WORDS: global positioning system (GPS), satellite navigation guidance, aeronautical navigation guidance, astronautical navigation guidance, and satellite surveying.

I. General Description of Developments in Satellite Navigation Guidance

On October 4, 1957, the first artificial satellite in human history, SPUTNIK 1, was launched by the Soviet Union. From radio tracking and observations of this satellite by scientists at the Laboratory of Applied Physics at Johns-Hopkins University in the United States, they discovered the relationship between doppler frequency shift and satellite motion, as measured by them. In further research, with sufficient understanding of the terrestrial gravity field and through observations on satellites

with known orbits, the observer's position can be determined. This is the concept of satellite navigation guidance. This concept is precisely what is required by the Polaris submarines of the United States, therefore a research team on a scheme of satellite navigation guidance was set up at the laboratory. In December 1958, the first research funds were granted; this was the inauguration of Transit research, the first-generation navigation guidance satellite system.

The first satellite under the Transit system was launched in September 1959; beginning in 1964, the United States Navy began deploying the satellites. In 1967, networking of the system was performed for civilian use. As the first-generation satellite navigation system, it solved a number of key technologies, such as power supply system, oscillator design, and experiments on gravity gradient stability, among others. Thus, the foundation of operations was accomplished. At this time, the system was mainly applied to the Army, Navy, and Air Force, as well as surveys for positioning offshore drilling platforms. The absolute precision can be 10m, while the relative precision can be 5m.

Although the Transit system basically satisfied the requirements at the time, however, there were still multiple problems, such as:

1. The system was unable to apply real-time navigation guidance; the time interval between two positionings was 1.5 to 4h.
2. The system was unable to guide the navigation of underwater vehicles.
3. The system was unable to provide three-dimensional positioning information and velocity.
4. The system was unable to position at all times. Positioning could be done only when a satellite passes overhead.
5. A period of little more than 10min was required for each

positioning, so it was not able to satisfy the requirements of a moving body.

Based on these shortcomings, the United States military proposed a revision scheme for the Transit system. At the same time, the Navy's Timation Project and Air Force's 621B system began to be developed in September 1964. In December 1973, both systems were combined into the present Navstar-GPS scheme.

Basically, GPS remedies the shortcomings of TRANSIT. This is because several key technologies are applied, for example: the ultrastable atomic clock technique, with stability of 10^{-4} . There were also the technology of crystal oscillators, to maintain satisfactory precision at a cost that users' equipment can cope with, in addition to precision Star Calendar tracking and forecasting techniques, in attaining positioning accuracy.

GPS applications were disseminated into many aspects of military and civilian applications. Further applications are still being continuously sought for, in the application range and depth, as well as indirect applications in many hybrid systems, that is, component systems based on GPS.

II. GPS Applications in Civil Aviation

Civil aviation represents the most important civilian users of satellite navigation guidance. Its application, research and experiments in civil aviation are almost synchronously progressing with developments in satellite navigation guidance systems. In a satellite navigation guidance plan announced in 1992 by the Federal Aviation Administration (FAA), the plan supports all civil aviation requirements over the seas, air routes, terminals, nonprecision airport approaches, precision airport approaches, autopilot landing, airport departures, and operational airport guidance, as well development and experiments

upgrading and feasibility. Moreover, the plan supports and regulates the operational sequence and standards to meet all requirements in the flight stage. The Future Aviation Navigation System (FANS) Committee of the International Civil Aviation Organization (ICAO) has confirmed the standing of the navigation satellite guidance system, and prescribed targets and missions to be carried out in stages. For the satellite navigation system, it will be the sole navigation guidance means of the over-the-ocean air routes, continental air routes, and terminals, as well as the enhanced systems or hybrid systems that will also be the means of airport surface guidance and means of precision airport approaches. Moreover, the other land-based radio navigation guidance facilities are being closed down step by step. Some European countries and research units are preparing to conduct tests on the GPS system and its accuracy, with the goal of establishing a global navigation satellite system in the 21st century in order to replace the microwave landing system. The Japanese government is also participating in these activities.

The global, round-the-clock, all-weather, precision, real-time and nearly continuous features of the satellite navigation guidance provide advantages that no other system can match. In addition, the traditional concepts and methods have been changed. The system can provide integrated services to civil airliners of navigation guidance and landing, and integrated service from the ground to high altitudes. Used for air route navigation guidance, and as one part of air traffic control, the system can change traffic crowding in air routes and can improve the separation of layers altitude-wise, to monitor aircraft in flight all the time, and to be used in airport approaches and landing. Not only is the landing equipment simple, such simple equipment can carry out variable glide routes to approach an airport by circling overhead, with the simultaneous operations of multiple runways, and to replace airfield radar for monitoring the

airfield, in addition to traffic control of various mobile vehicles and aircraft.

The equipment used for aerial navigation guidance has matured; multiple experiments were conducted on large aircraft, including the Boeing 747. The GPS hybrid system to be used in airport approaches and landing was also accomplished in 1989 in its first flight.

III. Applications in Aerospace

The satellite positioning system is the most ideal guidance and navigation system for spacecraft. The system can provide positioning, velocity, and attitude, capable of providing continuous services for spacecraft in launches, in-orbit operations, reentry, as well as approaching and landing. On these aspects, multiple experiments were conducted in the United States. The Space Shuttle is a manned reentry type spacecraft; its navigation guidance system requires very high accuracy and reliability; therefore, multiple redundancy and inertial guidance equipment are required, with redundancy of the TACAN microwave landing system, radar altimeters, atmospheric data machines, starlight trackers, and crew optical observation instruments, with redundancy for all these systems to perform combination and hybrid operations with redundancy. After the GPS is applied, the original systems can be greatly simplified. Satellite positioning can also be used in orbital determinations by low-orbiting satellites and space stations; difference GPS can be used to accomplish rendezvous and docking between spacecraft with the following advantages.

1. Reduce the number and simplify the earth observation stations and lower observation expenses.
2. Orbit updating can be conducted almost in real time to

the ground, to eliminate ground data processing, and to upgrade satellite working efficiency.

3. Reduce the various errors of the traditional surveying and control systems, such as electron wave propagation error, errors due to the earth's rotation, polar shift, gravitational shift, and the positions of the survey stations, among others.

4. The GPS satellite operates in a high orbit with good observational geometric relationship with the users in intermediate and low orbits, along with long tracking time.

Since 1982, a type of two-channel GPSPAC receiver was tried out on Landsat-4, Landsat-5, the Space Shuttle, and two U.S. Navy military satellites, with positioning accuracy between 5 and 10m, and accuracy of velocity measurement between 2 and 5cm/s. At present, research is underway on the dual-difference GPS interferometer for satellite orbit determination, as well as GPS/INS/starlight hybrid navigation guidance. These efforts can not only upgrade the precision of orbit determination, but can also be used for various satellites of intermediate and low orbits to users of geostationary orbits.

In China, tracking research on applications of GPS in the aerospace field began in the early eighties. The main activities were concentrated in the Aerospace Research Academy, and several aeronautical and astronautical institutes and schools, including discussion of schemes, research on algorithms, and improvements in simulation and hardware equipment. It can be said that by using the present equipment in China and abroad for guidance, orbit determination, and control of spacecraft, one can obtain an accuracy and convenience that cannot be attained with other kinds of equipment.

IV. Ocean Navigation and Maritime Applications

The oceans are one of the areas with the most application prospects for the satellite navigation guidance system. Militarily, with the exception of various types of navigation, all of the following can be accomplished with the satellite navigation system: guidance for ships, high-seas patrols, fleet maneuvering and rendezvous, maritime military exercises, and coordinated combat, launching of weapons, navigation guidance of aircraft carriers, and guidance of carrier planes. In the civilian field, ship positioning, high-seas surveying, petroleum prospecting, setting of buoys for oceanic fisheries, pipeline-laying, shoal surveying, positioning of hidden reefs, harbor pilotage, and maritime transportation and management can be performed by the system.

In maritime operations, at present the GPS has the most users in this area. Since 1980, a large number of experiments were conducted by the United States, Japan, Britain, Germany, France, and other countries. It is estimated that at the present time, there are 100,000 ships relying on navigation GPS guidance; this market is still rapidly expanding. Along the China coasts, fishermen also operate almost 10,000 GPS receivers. A special working team was formed by the navigation safety committee of the International Maritime Organization. Since 1984, multiple conferences were convened to evaluate applications of the GPS system. In maritime operations, there are no other more advanced systems than GPS. Therefore, great attention has been paid to its development and applications. Besides ordinary applications, the various precision positioning methods of the GPS will be used to monitor and control harbor ships, for navigation guidance of ships negotiating narrow channels, maritime geophysical prospecting, positioning of offshore platforms, establishment of navigation floats and buoys, as well as positioning for underwater objects, together with sonar.

V. Applications in Geodetic Surveying

For long-term observation of a point or for multiple-point networking observations with post-processing by using satellite positioning, observational accuracy at the centimeter level can be attained, thus providing new observational means for research into geodynamics, crustal movements, earth's rotation and tectonic plate movements, geodetic surveying, and seismic monitoring. Here, some special processing methods are used, such as the satellite source radio interference method, multiple-difference method, carrier wave phase observations, dual-frequency receivers, as well as smoothing and filter wave technique, in providing accurate and simple means for geodetic surveying, especially for the design and construction of highways, railways, and bridges.

Applications of GPS in geodetic surveying in China are the most extensive and mature. Not only have a large number of experiments been conducted, but a nation-wide surveying and control network was set up. On this aspect, large numbers of activities were performed at the Surveying and Cartography Institute of the General Staff Department, Surveying and Geophysics Institute of the Chinese Academy of Sciences, the Wuhan Surveying and Cartography University, and the Surveying and Cartography Academy of the People's Liberation Army. For example, as told in a report by the Surveying and Geophysics Institute of the Chinese Academy of Sciences, after the 1989 importing of the Ashtech receiver from the United States, the GPS shape-variation monitoring network for the reservoir area of the Three Yangtze Gorges was set up. The GPS is used to determine water level fluctuations in an area, and surveying of a control network in a municipality. At the aerial surveying group of the Geology Bureau in Shaanxi Province, GPS was used to conduct aerial surveying of the Hanzhong area in the province, and aerial surveying of a region in Shandong Province. GPS brings over

gigantic technical innovations in geodetic surveying, becoming a primary surveying means. Experiments and applications on using GPS to monitor earthquakes are underway in the United States, Japan, and Canada. In such activities, satisfactory achievements were attained in China. By the First Geology Terrain Variation Monitoring Center of the State Seismic Administration, 42 observation sites were set up in the North China area (107 to 122° E. Long., and 33.5 to 42° N. Lat.) in an area 1400km from east to west, and 400 to 800km from north to south, in a 700,000km² area covering Inner Mongolia, Shanxi, Hebei, Beijing, Tianjin, Liaoning, Shandong, and Jiangsu. By using the model Ashtech dual-frequency GPS receivers with continuous observation of long-term segments and multiple time segments to satisfactorily eliminate systematic errors due to meteorological factors and satellite constellation variations, in obtaining highly accurate observational results. In the late summer of 1990, in the Ya'an area of Sichuan Province, and in Western Yunnan in the year 1988, satisfactory results were recorded in earthquakes by using GPS observations.

VI. Applications in Land Navigation Guidance

Requirements are the lowest for land-navigation satellite systems; with time sequence processing by a dual- or single-channel receiver, positioning can be made on two dimensions or in one dimension (such as a train with fixed tracks), only two or three operating satellites are required. Even during suspension of operations because of signal interruption, no accidents such as happen with aircraft will take place, therefore the requirements on perfection of satellite systems are low. Landmarks and terrain can be used to update the data at all times. The estimation of navigation position and the additional information by using velocimeters are feasible. In recent years, with prices dropping for GPS receivers, GPS land users rose dramatically. Land navigation guidance will have the largest

number of GPS system users

Applications of land navigation guidance have the following aspects:

1. Positioning of motor vehicles together with an electronic digital map can provide the driver with his positions on various routes, service networks, and safety systems.

2. In the case of management of vehicles in business, such as leased vehicles, banks, public security, transportation, emergency first aid, and firefighting, the system can locate the position of a single vehicle and also provide vehicle operating information to the command and management departments.

3. Monitoring and control of trains: by using GPS to have unified dispatch and transportation management of various trains, safety can be ensured and the traffic flow can be increased.

4. Field operations, such as navigation guidance of vehicles and personnel in remote areas of deserts, high mountains, and forests.

5. Positioning of troop movements, such as vehicles, tanks, armored cars, artillery, and field combat troop units.

Land navigation guidance is also the earliest positioning experiment under GPS. At the Rockwell Corporation in the United States, the model NAVCORE 1 single-channel receiver was tested in an experimental field as well as on railroads from Fredwood to Gans and to Lake Kelly, and on rural highways for positioning experiments. There were structures, woods, bridges, tunnels, and city streets in the experimental site, with relatively poor environments. In 1984, motor vehicle positioning experiments were conducted on the TI4100 multichannel repetitive-use GPS receivers of the Texas Instruments Corporation, in the United States, and a navigation position estimation system for land vehicles by the Siemens Corporation, for motor vehicle positioning experiments in Munich, Germany. The experiments confirmed the system's feasibility. In recent years, the Chinese

press gradually reported on passenger car positioning with GPS in the United States, United Kingdom, France, Japan, and Germany. A prototype machine for a GPS/digital map was developed by the Xibei Industrial University; the machine was verified experimentally for use in traffic control of various commercial vehicles.

There are very good prospects for motor vehicle positioning by the GPS; however, some technical problems still have to be solved, such as signal attenuation due to electromagnetic interference, signal reflection, building barriers, and woods in the cities, as well as receiver prices, among other factors.

VII. Military Applications

At present, the major satellite navigation guidance systems, such as the GPS and GLONASS, are military products. For example, GPS is one of the projects with the most penetrating effects in the United States Department of Defense, capable of having technical innovations in strategy and tactics; however, civilian applications are only a byproduct. From its birth to the entire developmental process of the GPS, it has served military purposes. Dramatic results were obtained from the positioning of a single soldier, to detection of nuclear blasts in the vast military development project. However, due to the security classification of military scientific research accomplishments, we are not able to obtain this information. Moreover, most of the results are obtained in the range of the precision positioning system (PPS). China is unable to be such a licensed user, therefore this article limits the discussion to only a very small area.

Even before the accomplishments of system deployment, GPS was applied in actual combat. In the Gulf War, both sides applied GPS. In Iraq, positioning of mobile launch pads of Nike-

Ajax missiles was used. In the multinational troops, GPS receivers were supplied to personnel above company level among combat troops, as well as in various types of vehicles and special forces. GPS was applied in more than 20 aircraft models, such as fighters, bombers, interceptors, AWAC, command craft, submarine hunters, electronic warfare craft, helicopters, and in-flight refueling craft. During that period, the American military drafted 57,000 GPS receivers, including more than 400 sets of AN/WRN-6 (V) receivers, which were used for aircraft carriers and submarines.

Space defense is consistently the problem of most concern to the American military. For space flight vehicle surveying and control in definite time and space ranges, the Star Wars project planned to use GPS as the time and space positioning information system for space interceptors. GPS can provide accurate coordinates for battlefield management, C³I system, and the shared time multiple division access system.

Trajectory surveying of missiles and carrier rockets, as well as monitoring of target sites are one of the design functions by the American military on the GPS system. Numerous experiments were conducted since 1980; numerous models of missile-borne GPS receivers were developed, such as the MBRS and the AMR missile-borne receivers by the Texas Instruments Corporation to be deployed in the Minuteman missiles. GPS was used in cruise missiles to replace terrain-matching systems.

For GPS used in trajectory surveying and monitoring of target sites, the principle is simple, with convenient application, high accuracy, little effects by the meteorological environment, and economizing in equipment and personnel as a rapid data processing rate, especially capable of continuous whole-range monitoring on long-range missiles, for providing information on orientation and time synchronizing information.

These features cannot be matched by other equipment. Much work was done on such research.

The article will not list the applications of GPS in the land, sea, and air forces.

VIII. GPS and Flight Mechanics

On the space-technical basis, GPS is the most recent product, including present geodetic surveying, atmospheric surveying, high-frequency radio, digital communications, and computer application technologies. The development and application requires high-tech support of multiple disciplines. Flight mechanics plays a major role.

The deployment of the GPS positioning satellite network benefits from the following technologies, including classical flight mechanics in multidisciplinary knowledge, especially the determination of satellite orbits and positioning of carriers, prescribing of star calendars, and orbit updating model.

In GPS receiver software packages, flight mechanics and its related disciplines become the basis of the software algorithms, such as:

1. Unified global geodetic coordinate system, and conversion between various coordinate systems.
2. Universal gravitational model and error correction.
3. GPS satellite position calculation (forecasting by star calendar, updating model parameters).
4. Updating parameters for model of atmospheric propagation errors.
5. Time system and updating of the synchronizing system, and compensation due to the relativistic effects.
6. Optimal stellar selection, and
7. Mechanical compilation of position calculations.

In the development of high-level applications of GPS, the basis of flight mechanics should be adhered to. At present the following topics are under study:

1. Design of difference-GPS, including design of difference-stations, difference-format and algorithms, and updating of long-distance effects.
2. Related dynamical problems when GPS is applied by highly mobile carriers.
3. Application of GPS in trajectory surveying and target site surveying.
4. Kalman filtration problems related to processing GPS signals.
5. Problems of combining GPS and other systems.
6. GPS applications in hybrid guidance, and
7. Determination of carrier attitude by GPS and study of the deformation problems of large structures subject to bending.

We can see that the GPS research especially the development of high-level applications, flight mechanics is one of the main pillars. We should vigorously develop research and applications so that GPS can be applied by the military and civilian departments in China as early as possible.

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